INVESTIGATION OF FIRE-VULNERABILITY-REDUCTION EFFECTIVENESS OF FIRE-RESISTANT DIESEL FUEL IN ARMORED VEHICULAR FUEL TANKS

FINAL REPORT
AFLRL No. 130

by

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Laboratory flammability tests and bench-scale ballistic tests are described which have been used in the development of fire-resistant diesel fuel (FRF). These tests have indicated that FRF, at a bulk liquid temperature of 77°C, would be self extinguishing even if the flash point of its base fuel was less than 62°C. In order to confirm that this self-extinguishing property would prove effective in a realistic combat environment, arrangements were made for a series of tests to be conducted by New Mexico Institute of Mining

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and Technology. These tests utilized 3.2-inch precision shaped charges fired through the armor and internally mounted fuel tanks of M48 battle tank and M113 armored personnel carrier hulks. Warheads were obtained by USAMERADCOM, and AFLRL personnel participated in the planning and conducting of the tests, including all FRF blending.

Results of the full-scale tests confirmed that residual burning can be eliminated by the use of FRF even though the mist fireball development is similar to that of neat fuel. Transient pressure effects are not affected by FRF, but sustained temperatures are drastically reduced by the FRF self-extinguishment.

FOREWORD

This report was prepared at the U.S. Army Fuels and Lubricants Research Laboratory (AFLRL), Southwest Research Institute, under DOD Contract No. DAAK70-79-C-0215. The project was administered by the Fuels and Lubricants Division, U.S. Army Mobility Equipment Research and Development Command (MERADCOM), Fort Belvoir, Virginia 22060, with Messrs. F.W. Schaekel and J.V. Mengenhauser, DRDME-GL, serving as Contracting Officer's Representatives. For this program, 3.2-inch shaped charge warheads were obtained by MERADCOM from U.S. Army Ballistic Research Laboratory (BRL). This report covers the period of performance from 25 September 1979 to 31 September 1980.

Acknowledgement is given to Mr. J.P. Pierce for conducting 20-mm HEIT ballistic tests and backup flammability experiments and assistance in conducting full-scale ballistic tests. Special acknowledgement is given to Messrs. M.E. LePera, F.W. Schaekel, R.D. Quillian, Jr., and S.J. Lestz for their participation, encouragement, and suggestions. Acknowledgement is given to Mr. J.W. Pryor and Ms. E.J. Robinett for editorial assistance in producing this report.

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I. INTRODUCTION

The U.S. Army has a special requirement for a diesel fuel which will perform satisfactorily in diesel-powered combat vehicles but would self-extinguish in case of ignition by ballistic penetration or other unwanted ignition sources. The main thrust for this investigation was experience gained in Southeast Asia and in the 1973 Arab-Israeli conflict, which indicated that fuel fires can be a major cause of ground vehicle and personnel losses. These results, which were obtained from studies conducted by the Survivability Office at U.S. Army Material Systems Analysis Activity (AMSAA)[(1)*], indicated that, if catastrophic fuel fires could be eliminated, personnel would have increased chances for survival, and chances of repair or salvage of vehicles would be improved. Thus, cost effectiveness would be realized not only in reduced key personnel losses, but also through improved supply of critical tactical equipment in an area where resupply may be impossible.

A. Background Information

Six generations of fire-resistant fuel have been investigated by the Army, and these are summarized in Table 1.[(2,3)] The last approach was selected for developing fire-resistant fuels (FRF) for diesel-powered ground equipment. The selected approach involves the inclusion of surfactant-stabilized emulsified water in diesel fuel. Screening studies followed by laboratory, bench-scale, and full-scale experimental investigations have led to the development of clear-to-hazy fire-resistant microemulsions of 10 vol% water and 6 vol% surfactant formulated in DF-2 diesel fuel. The surfactant comprises a mixture of reaction products formed from two moles of diethanolamine and one mole of oleic acid, or 1.009 moles of oleic acid in a modified version of the surfactant.

Because of complexities resulting from variations in the composition of the base fuel, emulsifying agents, and water, extensive laboratory evaluations of physical and chemical properties have been an essential element of the FRF development program. It should be mentioned that the development of the surfactant required to produce the FRF blend has been based on typical fuel formulations--not on modifying the fuel to accommodate the surfactant.

* Superscript numbers in parentheses refer to the list of references at the end of this report.

TABLE 1. SIX GENERATIONS OF FIRE-RESISTANT FUEL FORMULATIONS INVESTIGATED BY THE U.S. ARMY

1. Fuel gellation just prior to hazard occurrence (Initiated by U.S. Army Aviation Material Laboratories--1964-1966).

2. Semisolid, but pumpable, fuel-in-water emulsions (Initiated by U.S. Army Aviation Material Laboratories--1965-1970).

3. Viscous-liquid, fuel-in-water emulsions (Initiated by U.S. Army Coating and Chemical Laboratories--1969-1972).

4. High molecular weight polymeric additives for inhibition of mist formation (Initiated by U.S. Army Coating and Chemical Laboratories--1971 →).

5. Volatile halogenated fire suppressant as fuel constituent (Initiated by U.S. Army Ballistic Research Laboratories--1972-1976).

6. Nonviscous, water-in-fuel emulsions (Initiated by Fuels and Lubricants Division, Energy and Water Resources Laboratory, U.S. Army Mobility Equipment Research and Development Command--1976 →).

Laboratory evaluations have also included determinations of thermal stability, surface tension, electrical conductivity, low-temperature flow properties, foaming, and elastomer compatibility. Table 2 is a comparison of properties

TABLE 2. REFEREE-GRADE-BASE-FUEL FRF SPECIFICATION-TYPE PROPERTIES

Referee-Grade Base Fuel MIL-F-46162A(MR)II	Neat Base Fuel	Base Fuel Plus 10 vol% Water Plus 6% Surfactant
Gravity at 15.6°C, °API	36.1	36.1
Density at 15.6°C, g/ml	0.844	0.857
Cloud Point, °C	-21	--
Pour Point, °C	-24	-23
K. Viscosity (37.8°C), cSt	2.17 at 40°C	3.52
ASTM Distillation (D 86), °C		
Initial Boiling Point	166	---
10% Distilled	219	---
50% Distilled	244	---
90% Distilled	296	---
End Point	358	---
Carbon Residue on 10% bottoms, wt%	0.15	0.20
Sulfur, wt%	0.35	0.29
Cu Strip Corrosion, 3 hr at 50°C	1A	1A
Ash, wt%	0.01	0.00
Neut. No., mg/100 ml	0.01	0.74
Aromatics, vol% (FIA)	27.5	23
Heat of Combustion, Gross, J/kg	42.3×10^6	36.6×10^6
Cetane No.	48	41
Existent gum, mg/100 ml	3.9	1100

of a referee grade fuel and the FRF blend made from that fuel. Several different flammability evaluation procedures were employed to define the vulnerability characteristics of FRF candidates(2,3,4), and the results for referee-grade base fuel FRF formulations are summarized in Table 3. These flammability evaluations demonstrated that such aqueous microemulsions yielded diminished mist flammability while either eliminating pool burning or providing rapid self-extinguishment of pool fires, even at fuel temperatures more than 10°C above the base fuel flash point. Bench-scale ballistic tests, using 20-mm high-explosive incendiary tracer projectiles, and preliminary full-scale ballistic tests, using 3.2-inch precision shaped charges, correlated with the flammability data.

TABLE 3. REFEREE-GRADE-BASE-FUEL FIRE-RESISTANT FUEL FLAMMABILITY PROPERTIES

Referee-Grade Base Fuel MIL-F-46162A(MR)II	Neat Base Fuel	Base Fuel Plus 10 vol% Water Plus 6% Surfactant
Flame propagation across bulk liquid surface at 77°C	Wick burning with simultaneous propagation	Wick burning only
Burns on wick at 25°C	Yes	Yes
Flammability of fuel mist at 25°C (Mist Flashback Test)	Extreme	Moderate
Ballistic tests at 77°C (20-mm HEIT)	Catastrophic fire	Transient fireball with self-extinguishing ground fire
Flash Point, °C	61	65*
Fire Point, °C	91	---
Autoignition Temperature, °C	224	405

* Pilot flame in Penske Martens apparatus often extinguished by water vapor.

Diesel engine and turbine combustor performance tests have been conducted in which no difficulties were encountered in starting, idling, and running on FRF formulations under typical operating conditions. As would be expected from the water content, relative to the base fuel case, higher total fuel flow rates are required to produce equivalent power. However, in diesel engines, full power can be generated with these microemulsions by adjustment of maximum fuel rate settings in those diesel engines where such adjustment is feasible.

Performance of these fuel formulations has been evaluated in several different laboratory single-cylinder and multicylinder engines without alteration of injection timing, injection duration settings, or compression ratio. Performance comparisons are presented in Figure 1. Also, successful 250-hour en-

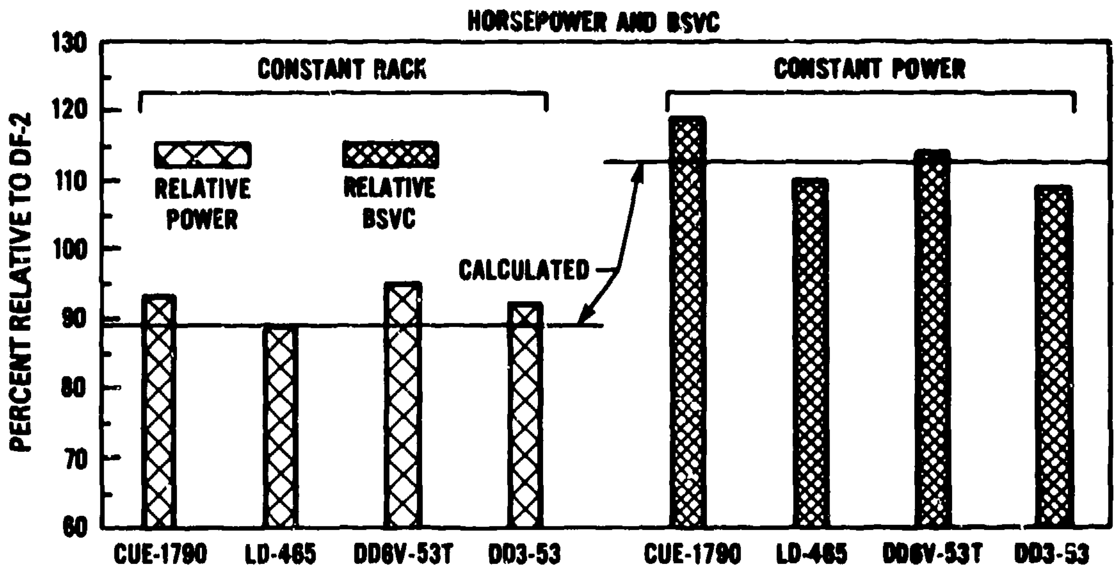


FIGURE 1. PERFORMANCE OF FIRE-RESISTANT FUEL VERSUS REFERENCE DF-2

durance tests have been conducted in a single-cylinder version of the 12-cylinder AVDS-1790-2C M60 tank engine. Results of these tests indicate that, depending upon the specific engine and its operating conditions, work cycle efficiencies may remain about the same or increase somewhat when FRF formulations are used. Diesel engine exhaust measurements indicate increases in unburned hydrocarbons, no change or increases in carbon monoxide, no change or

decrease in nitrogen oxides, and no change or decreases in particulates and smoke. Similar measurements on the gas turbine combustor exhaust gases indicate reduced temperatures, increased unburned hydrocarbons, increased carbon monoxide, and decreases or no change in smoke.

FRF formulations have been observed to be noncorrosive to carbon steel, aluminum, and most other metals and alloys. However, because of the amine content, they have been found to be corrosive toward copper and its alloys. This incompatibility with copper has been alleviated by the addition of trace quantities (100-200 ppm) of an aryltriazole.

B. Objectives of Investigation

The purpose of the full-scale ballistic tests described in this report has been to evaluate the fire-resistant diesel fuel (FRF) under realistic conditions typical of those encountered in combat and to provide confirmation of bench-scale laboratory flammability and ballistic tests. Results also are expected to provide guidance for future development or modification of laboratory flammability/vulnerability evaluation techniques.

II. APPROACH

A. Liaison With Military and Industrial Organizations Planning Full-Scale Ballistic Evaluations of Armored Vehicular Fuel Tanks

During the initial phase of this program, contact was established with persons and organizations planning to conduct full-scale ballistic tests of armored vehicles to propose interfacing this program with such ongoing programs. Since the ballistic threat to military combat vehicles varies with the types of vehicle, no one facility was planning to evaluate all types of military vehicles. Also, it was ascertained that planned full-scale tests would not be conducted during the period of performance of this contract. Accordingly, it became evident that a special series of full-scale ballistic evaluations would be required to meet the objectives of this program.

B. Bench-Scale Laboratory Flammability and Ballistic Tests

Existing flammability/vulnerability property data, which are to be confirmed by full-scale FRF ballistic tests, have been evaluated with bench-scale laboratory flammability and ballistic tests developed by AFLRL. These techniques are briefly described in the following paragraphs.

It has been shown in the laboratory that mist flammability and pool-burning effects can be evaluated by the AFLRL impact-dispersion technique, which is illustrated in Figures 2 and 3.[2,3] Impact-dispersion experiments are conducted in a well-ventilated, enclosed facility developed for this purpose (see Figure 2). These tests involve allowing a 2-liter glass vessel, containing about 1.2 kg of fuel, to fall freely 6 meters onto a steel target plate with the point of impact being surrounded on two sides by gas pilot flames. The target plate comprises a horizontal (see Figure 3), elevated 2.5-cm thick steel plate with electric surface heaters attached to its underside so that its upper surface temperature can be adjusted and controlled.

The glass containers are filled to an ullage of about 2 percent of the total volume for each test. A television camera, located about 6 meters from the impact point, is used to document test results on video tape. A background grid provides a dimensional frame of reference, and subsequent examination of the videotape by slow motion (and stop action) provides reduced data. Tests are conducted at several different temperatures, from about 25° to 99°C, by preheating the fuel sample and the steel target plate independently to the desired temperatures. This procedure has been shown to provide a quick, inexpensive, repeatable method for evaluating mist flammability and pool-burning characteristics of fluids.

The most severe flammability test presently conducted at AFLRL is the 20-mm HEIT ballistic test.[2,3,4] This ballistic test is a relatively inexpensive procedure developed to provide a means for evaluating the relative fire vulnerability of various fluids of interest for Army applications. The technique employs 20-mm high-explosive-incendiary-tracer projectiles fired into partly filled fluid containers. It yields repeatable results which establish both transient fireball effects and residual pool-burning tendencies. The balli-

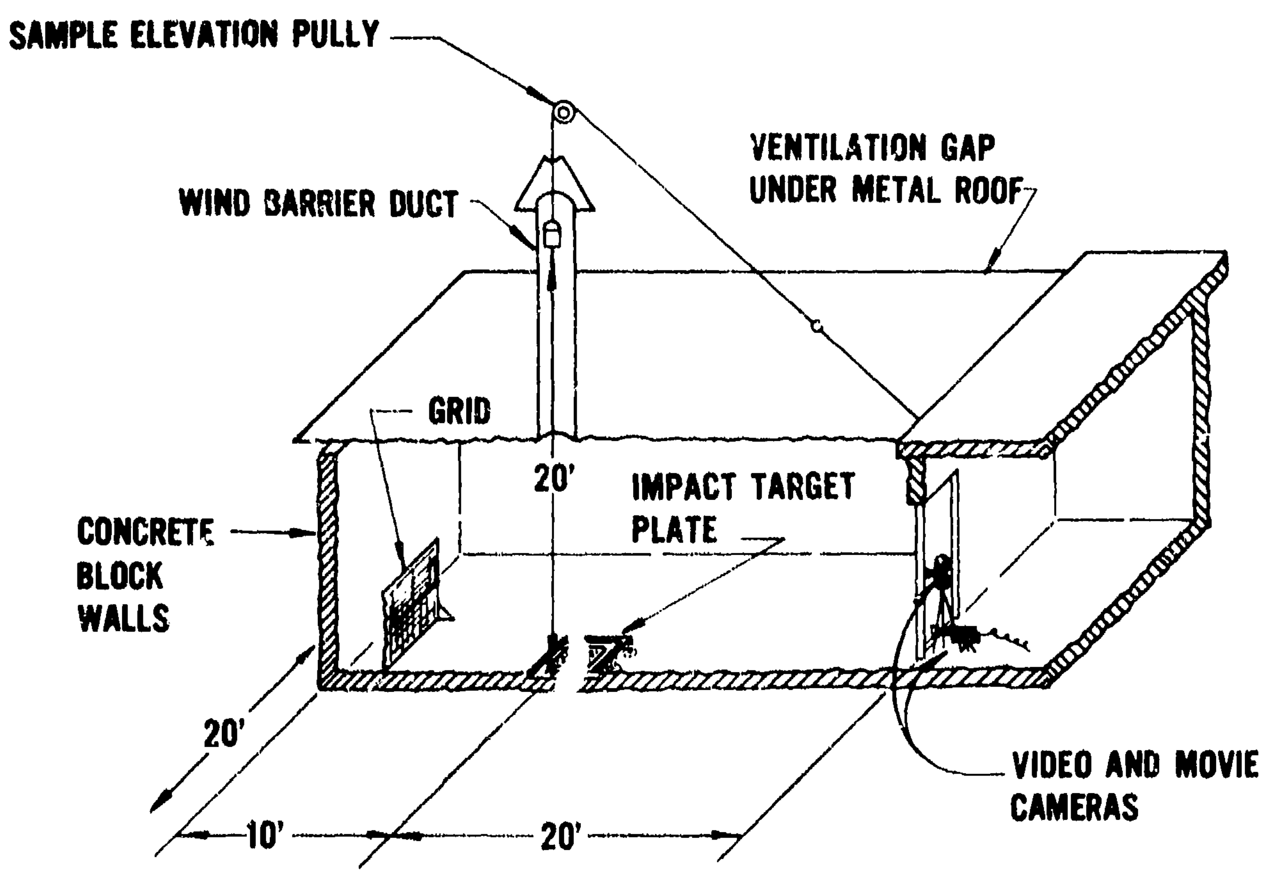


FIGURE 2. ILLUSTRATION OF IMPACT DISPERSION TEST FACILITY

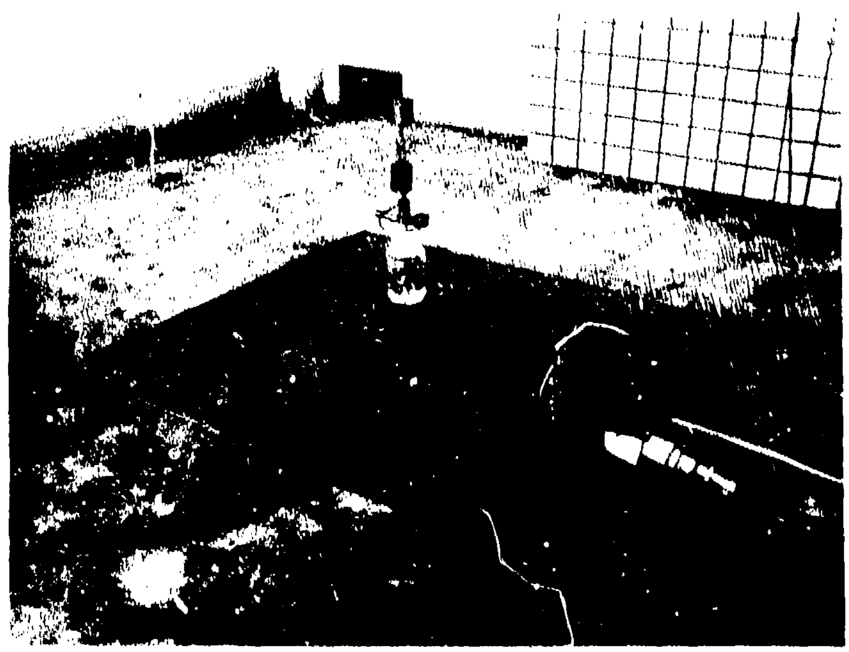


FIGURE 3. IMPACT PLATE AND PILOT ARRAY WITH SAMPLE AND SOLENOID RELEASE MECHANISM LOWERED FOR DISPLAY

stic test procedure utilizes three major components: a 20-mm Mann rifle assembly; a fuel tank target, including an actuator plate; and video and 16-mm movie film recording equipment. Figure 4 illustrates the overall experimental setup. The hemicylinderical target enclosure is constructed from corrugated steel culvert pipe, 0.3-cm thick, 4.6-m wide, 2.7-m high, and 3.3-m deep. The 20-mm Mann rifle assembly is located under an open shed with the rifle barrel being mounted in a universal cradle. All firings and high-speed 16-mm recordings are remotely triggered by a solenoid. A real-time 16-mm motion picture camera and a video recorder are used also to document the events following impact.

Figure 5 illustrates the fuel target assembly. The target is an expendable 114-liter steel drum meeting DOT-17E-203-73 specifications This moderately priced target provides consistent responses to the ballistic impact. Projectile impact plates are placed 0.3 m in front of the face of the drum to serve as fuse actuator plates. These 0.3-m square plates are fabricated from 0.6-cm thick 6061-T6 aluminum.

A relatively high fluid test temperature (77°C) was selected for this test with the objective of providing a severe fire-hazard exposure. Military studies have reported bulk fuel-temperatures up to about 77°C in desert operations. On this basis, the test procedure has appeared to provide realistic assessment of the ballistic vulnerability of candidate fire-resistant fuels. The repeatability and reliability of the method have been shown to be satisfactory.

C. Use of Actual Armored Vehicles and Their Fuel Tanks for Full-Scale Evaluations

Arrangements were made for a series of full-scale ballistic tests to be conducted by the TERA group of New Mexico Institute of Mining and Technology, Socorro, NM. These tests utilized 3.2-inch precision shaped charges fired through the armor of a battle tank hulk (M48) and a personnel carrier hulk (M113) into the fuel tank mounted against the interior wall of the vehicle.

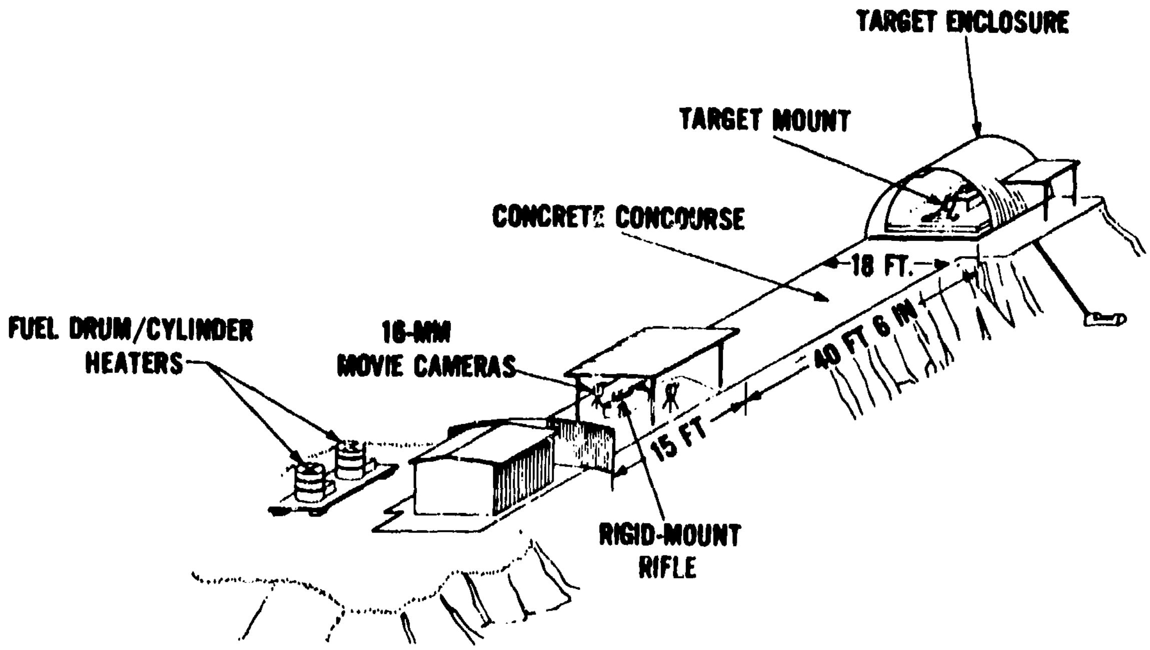


FIGURE 4. ILLUSTRATION OF BALLISTIC RANGE USED FOR 20-MM HEIT EVALUATIONS

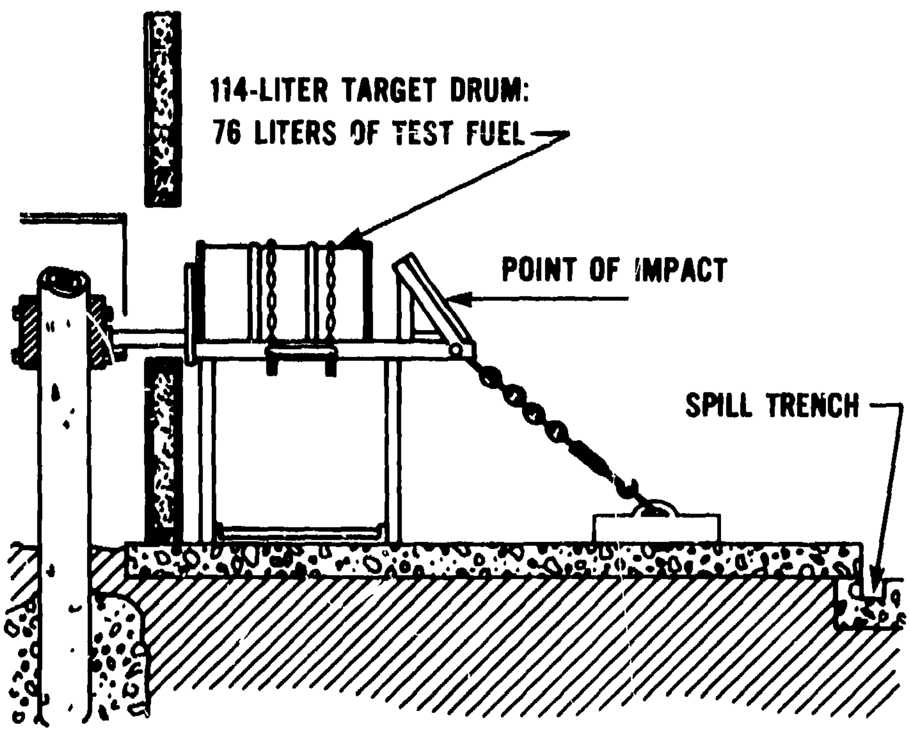


FIGURE 5. ILLUSTRATION OF FUEL DRUM TARGET ASSEMBLY

Warheads were obtained by USAMERADCOM from U.S. Army Ballistic Research Laboratories (USABRL), and extra fuel cells for the M113 were fabricated by TERA. Diesel fuel was furnished by TERA, as purchased from local suppliers, and a dedicated fuel tank was provided for its storage. AFLRL provided a water deionizer system and surfactant, and AFLRL personnel participated in the planning and conducting of the tests, including conducting all FRF blending.

III. FULL-SCALE FUEL TANK EVALUATION PROGRAM

A. Fuel System Vulnerability Review

A review of the vulnerability of the fuel systems indicated that specific systems are vulnerable to specific types of ammunition. The major threats to armored vehicles, such as tanks and armored personnel carriers, are antiarmor warheads and missiles, whereas small arm projectiles are normally used against jeeps and trucks. The fuel storage tanks on combat vehicles such as the M48 and M60 battle tanks are located on both sides of the engine compartment. The results of a projectile entering this compartment is particularly severe since the fuel can be ignited not only by the projectile but other sources such as the hot manifold or electrical shorts. Another factor is that the fuel is not only heated by recycling through the engine but also by heat radiated from the engine. The location of the fuel cells in the M48 engine compartment temporarily provides a reduced hazard to the crew since there is a firewall separating them from the engine compartment. However, the spillage and ignition of several hundred gallons of fuel would destroy the vehicles, and possibly crew members, if the fire is not extinguished. Armored personnel carriers, however, have their fuel tanks located within the personnel compartment, and any ballistic penetration causes severe damage to both personnel and the vehicle. If a combat vehicle contained a fire-resistant fuel, it would greatly improve chances of crew survival, especially wounded, immobile personnel. Also, if no sustained burning of the spilled fuel occurred, damage to the vehicle would be minimal.

B. Full-Scale Ballistic Tests

A series of seven tests was conducted using 3.2-inch precision shaped charges with the M113 and M48 armored vehicles (See Appendix). The fuel used in the

tests conformed to DF-2 specifications, but only those properties that would relate to flammability characteristics were measured. Those measurements included flash point and ASTM D 86 distillation. It was interesting to note that the flash point of the fuel was 54°C and the test temperature was expected to be 77°C. This represented the first time that this extreme difference between base fuel flash point and fuel test temperature would be evaluated. However, based on flammability test results previously obtained in the laboratory, it appeared that the fuel should self-extinguish under the proposed test conditions.

The data recorded in this series of ballistic tests included 16-mm movie coverage (both real time and high-speed), pressure measurements, and vehicular interior temperature. The overall positioning of the cameras and sensors is shown in Figure 6. As is shown in the figure, there were two cameras (real time and high-speed) covering exterior response to ballistic penetration of both the M113 and the M48 tank. However, inside cameras were only used with the M113 since the crew compartment of the M48 is separated from the engine compartment by a solid firewall. Pressure and temperature measurements were made in both the M113 and M48 tests.

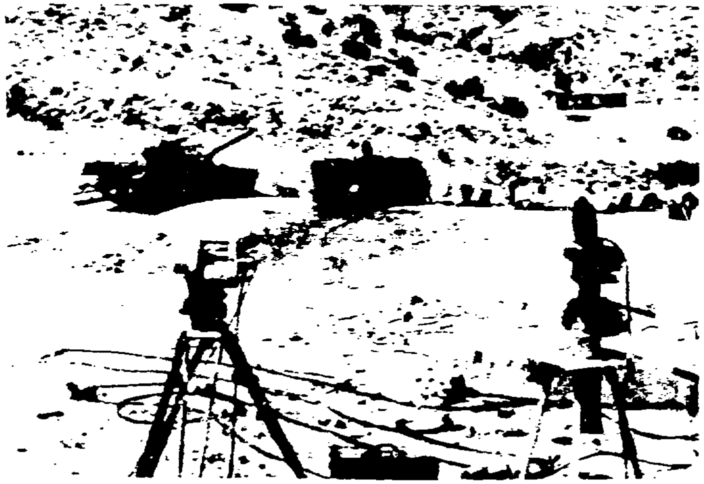
The overall results indicate that the FRF blends successfully eliminated the catastrophic residual burning that was observed using neat fuel. Similar results were obtained in both the M113 armored personnel carrier and the M48 tanks. Each test is briefly discussed as follows.

M113 Armored Personnel Carrier Tests

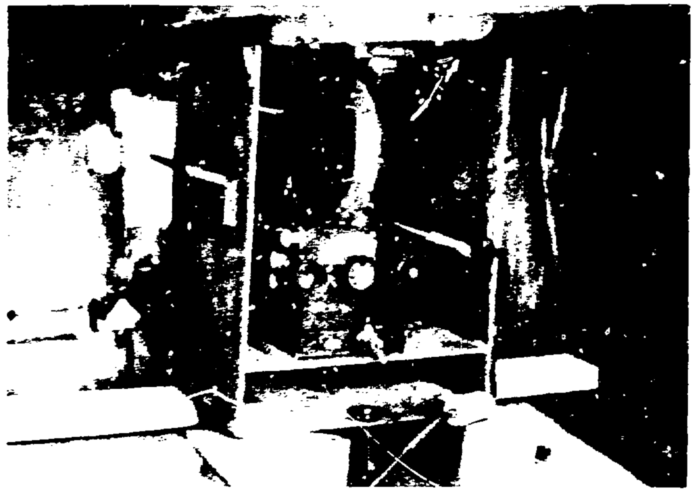
Test 1

(AZ041A0)

Vehicle Configuration: Ramp closed.
Fuel: Neat fuel--flash point 54°C(130°F).
Fuel Test Temperature: 77°C(170°F) approximately.
Fuel Volume: 230 liters (60 gal.) fuel, tank volume is approximately 300 liters (80 gal.).

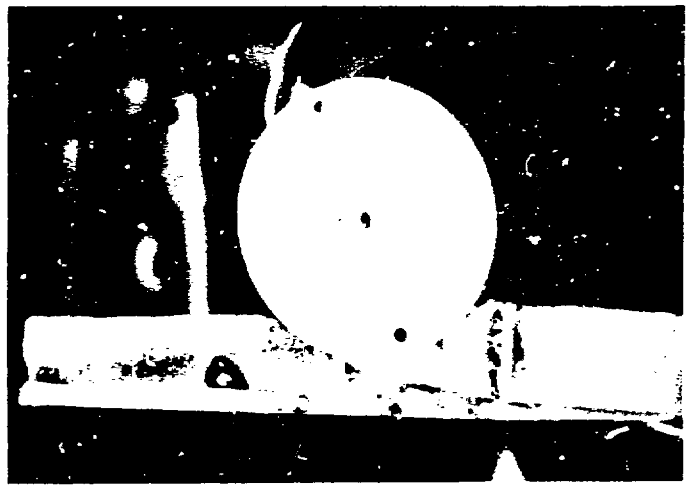


EXTERNAL SLOW-MOTION AND
REAL-TIME CAMERAS



SHIELDED CAMERA IN ENGINE
COMPARTMENT

PRESSURE/TEMPERATURE SENSOR AND
CAMERA VIEW PORTS



PRESSURE/TEMPERATURE SENSOR

FIGURE 6. INSTRUMENTATION FOR M113 ARMORED PERSONNEL CARRIER BALLISTIC TESTS USING 3.2-INCH PRECISION SHAPED CHARGES

Type Projectile: 3.2-in. precision shaped charge.

Test Results: A large mist fireball was observed upon impact followed by residual burning within the crew compartment and engine compartment (housing the interior cameras). As fuel continued to slowly spill on the ground, a large amount of pool burning occurred, virtually engulfing the vehicle. Fire department assistance was required to extinguish the fire.

Interior Temperature: 565°C(Sustained).

Interior Pressure: 12 psi.

Test 2

(AZ0421A0)

Vehicle Configuration: Ramp closed.

Fuel: FRF

Fuel Test Temperature: 77°C(170°F) approximately.

Fuel Volume: 230 liters; tank volume is approximately 300 liters.

Type Projectile: 3.2-in. precision shaped charge.

Test Results: A large mist fireball was observed upon impact, however, essentially all pool burning was eliminated. A very small amount of burning in the camera area (apparently involving materials other than diesel fuel) required extinguishment. No evidence of pool burning outside of vehicle was noted.

Interior Temperature: 343°C (Transient).

Interior Pressure: 11 psi.

Test 3

(AZ0421B0)

Vehicle Configuration: Ramp Open.

Fuel: Neat fuel--flashpoint 54°C(130°F).

Fuel Test Temperature: 77°C(170°F) approximately.

Fuel Volume: 230 liters; tank volume is approximately 300 liters.

Type Projectile: 3.2-in. precision shaped charge.

Test Results: The large ramp forming the rear closure of the vehicle was opened for this series of tests. The reasoning for this configuration was to determine if oxygen starvation could be causing the FRF to self-extinguish.

This configuration did seem more severe as evidenced by a larger mist fireball and more rapidly developing total pool burning of remainder of fuel.

Interior Temperature: 650°C (Sustained).

Interior Pressure: 11 psi.

Test 4

(AZ0422A0)

Vehicle Configuration: Ramp Open.

Fuel: FRF

Fuel Test Temperature: 77°C(170°F) approximately.

Fuel Volume: 230 liters, tank volume is approximately 300 liters.

Type Projectile: 3.2-in. precision shaped charge.

Test Results: A large fireball developed upon impact which was observed inside and outside of the vehicle. The same ramp configuration was used as described in Test No. 3. In reality, this test could be considered more severe than Test No. 2 since the size of the fireball is considerably larger than when the ramp is closed. It is this mist fireball that is considered the primary ignition source for subsequent pool burning. The FRF blend, however, was self extinguishing after the initial fireball, and no pool burning was observed.

Interior Temperature: 65°C (Transient).

Interior Pressure: 25.5 psi (sensor probably struck by flying debris).

M48 Battle Tank Tests

The next series of tests was conducted using the M48 tank. The actual fuel cells from the vehicle were used in this series. The total volume of fuel in the M48 tank is approximately 800 liters and is divided into four fuel cells, two on the side wall and two on the floor in the engine compartment. The larger of the side tank holds approximately 340 liters and the smaller holds approximately 170 liters. In this series, two of the large side-wall fuel cells and one of the small side-wall fuel cells were used. The engine was installed in its normal position for each test.

Test 5

(AZ0422B0)

Fuel: Neat fuel--flashpoint 54°C(130°F).

Fuel Test Temperature: 77°C(170°F) approximately.

Fuel Volume: 300 liters, tank volume is approximately 340 liters (large tank).

Type Projectile: 3.2-in. precision shaped charge.

Test Results: A large fireball resulted when the shaped charge exploded. It was diminished, from exterior view, since the blast occurred within the engine compartment. A large ground fire did develop, somewhat slowly, however. This burning was extinguished by the fire fighting crew.

Interior Temperature: No change.

Interior Pressure: No change.

Test 6

(AZ0424A0)

Fuel: FRF

Fuel Test Temperature: 77°C(170°F) approximately.

Fuel Volume: 150 liters (small tank).

Type Projectile: 3.2-in. precision shaped charge.

Test Results: A large fireball occurred when the shaped charge exploded. There was no residual fire from burning fuel. A very small amount of residual burning occurred in the vicinity of the hydraulic fluid reservoir and was attributed to accumulated hydraulic fluid.

Interior Temperature: No change.

Interior Pressure: 3.25 psi.

Test 7

(AZ0425A0)

Fuel: FRF

Fuel Test Temperature: 77°C(170°F) approximately.

Fuel Volume: 320 liters (large tank).

Type of Projectile: 3.2-in. precision shaped charge.

Test Results: A large fireball occurred from the shaped charge ignition; however, when personnel arrived upon the scene, no residual burning was observed.

Interior Temperature: No change.

Interior Pressure: No change.

Special Observations

The purpose of the full-scale tests was to evaluate the FRF blends in a realistic environment. Several factors could have had some adverse effects upon the results. In one case, the shaped charge penetrated the 3-in. exterior armor, passed completely through the fuel cell, and then burned through the engine crankcase into the empty fuel cell on the opposite side. It is quite conceivable that if there had been oil in the crankcase, it would have ignited and could have resulted in residual burning. In another instance, test No. 6, the shaped charge burned through the air cleaner and spilled oil into the engine compartment. It was possible that this oil was what was observed burning in test No. 6 and not hydraulic fluid. There are also other flammable materials that could have ignited and could have resulted in continued burning. This series of tests was considered especially successful since none of these events occurred.

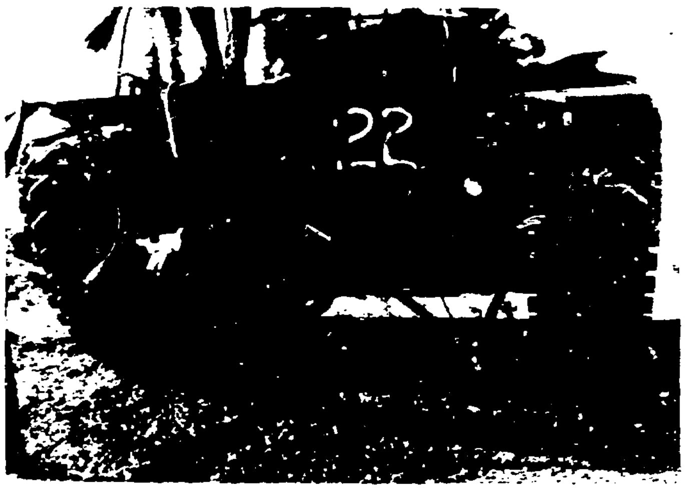
IV. DISCUSSION OF RESULTS

The purpose of these full-scale ballistic tests was to evaluate the FRF in a realistic situation. When extrapolation is attempted from laboratory results to full-scale evaluations, it is very difficult to account for every important parameter such as fuel volumes, spillage rates, debris collection, and others. It should be emphasized that every effort was made to conduct these tests with as much realism as was possible such as by using actual fuel tanks and reinstalling the engine for each test of the M48 battle tank.

The test series can be summarized by Figures 7 and 8. Figure 7 illustrates the results obtained with the M48 battle tank. In one case, there was no residual burning; however, with the neat fuel, the entire vehicle would have been destroyed without the assistance of a fire-fighting crew. The location

PREPOSITIONED SHAPED CHARGE

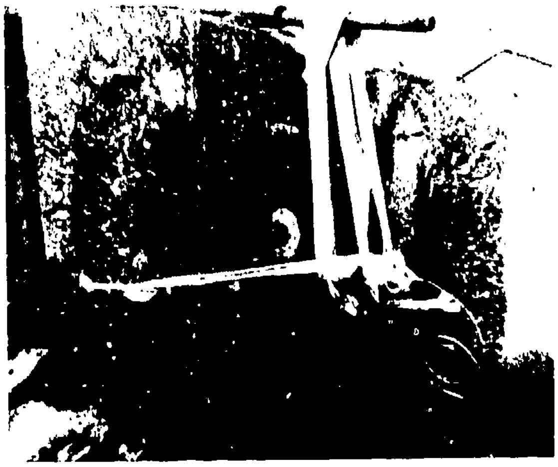
RUPTURED FUEL TANKS AFTER NEAT FUEL TEST



DRAINING OF NONIGNITED FUEL AFTER FRF TEST

FLAMING WITHIN AND BENEATH VEHICLE DURING NEAT FUEL TEST

FIGURE 7. DEMONSTRATION OF EFFECTIVENESS OF FIRE-RESISTANT DIESEL FUEL (FRF) AT 77°C IN M48 BATTLE TANK USING 3.2-INCH PRECISION SHAPED CHARGES (54°C BASE FUEL FLASH POINT)



PREPOSITIONED SHAPED CHARGE

FRF NEAT FUEL
RUPTURED FUEL TANKS AFTER TEST

DRAINING OF NONIGNITED FUEL AFTER FRF TEST

FLAMING WITHIN AND BENEATH VEHICLE DURING NEAT FUEL TEST

FIGURE 8 DEMONSTRATION OF EFFECTIVENESS OF FIRE-RESISTANT DIESEL FUEL (FRF) AT 77°C IN M113 ARMORED PERSONNEL CARRIER USING 3.2-INCH PRECISION SHAPED CHARGES (54°C BASE FUEL FLASH POINT)

of the fuel tanks within the engine compartment had a beneficial effect and a negative effect. Since the compartment is enclosed, the fuel fire developed slowly due to lack of oxygen and surface area for ignition. In fact, the development of the fuel fire took considerably longer than did the fire in the M113 vehicle. Benefits of this fuel tank location is the shielding of the personnel from the mist fire, allowing more time for extinguishment or escape. However, since the area is enclosed, the fire is more difficult to combat and the engine, during service, supplies a variety of different ignition sources.

Figure 8 shows the results obtained when the M113 armored personnel carrier was tested. It is obvious from the photograph that there was interior burning in the case of the charred fuel tank and no burning in the tank that looks bright. Actually, the interior temperature of the vehicle with the charred tank reached 650°C and the test resulting in the bright tank reached only 65°C. It would be safe to say that if personnel survived the fragment blast, their chances of survival would be greatly enhanced when no residual burning occurred. Obvious benefit in equipment salvageability would be achieved if pool burning could be eliminated.

V. CONCLUSIONS AND RECOMMENDATIONS

This series of ballistic tests has shown that catastrophic fires in armored combat vehicles can be eliminated by the use of fire-resistant diesel fuel. The obvious savings in personnel and equipment could more than justify the added cost of the modified fuel, especially considering the average time spent in combat. The results of this investigation can be summarized as follows:

1. Residual burning can be eliminated by the use of FRF.

2. Mist fireball development is similar for both neat and FRF fuels.

3. Transient temperatures are similar since the mist fireball development is similar.

4. Sustained temperatures are drastically different since the neat fuel continues to burn both inside and outside of the vehicle.

5. Fragmentation-shrapnel dispersal is not influenced by the presence of FRF.

6. Compartmental overpressures are not affected by FRF, and the pressure measurements during this series of tests indicated that overpressures may not be a problem.

VI. REFERENCES

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2. Weatherford, W.D., Jr., Fodor, G.E., Naegeli, D.W., Owens, E.C., Wright, B.R., and Schaekel, F.W., "Army Fire-Resistant Diesel Fuel," presented at SAE Fuels and Lubricants Meetings, Houston, TX, SAE Paper No. 790926, 1-4 October 1979.

3. Weatherford, W.D., Jr., Fodor, G.E., Naegeli, D.W., Owens, E.C., Wright, B.R., and Schaekel, F.W., "Development of Army Fire-Resistant Diesel Fuel," Interim Report AFLRL No. 111, prepared by U.S. Army Fuels and Lubricants Research Laboratory, Southwest Research Institute, under U.S. Army Contract Nos. DAAK70-78-C-0001 and DAAK70-80-C-0001, Government Accession No. AD A083610, December 1979.

4. Wright, B.R. and Weatherford, W.D., Jr., "A Technique for Evaluating Fuel and Hydraulic Fluid Ballistic Vulnerability," prepared by Southwest Research Institute, U.S. Army Fuels and Lubricants Research Laboratory, under U.S. Army Contract No. DAAK70-78-C-0001, Report AFLRL No. 89, Government Accession No. AD A055058 , December 1977.

APPENDIX

NMT/TERA NO. 80-1354-U

"INVESTIGATION OF FIRE-VULNERABILITY-REDUCTION-EFFECTIVENESS OF FIRE-RESISTANT DIESEL FUEL IN ARMORED VEHICULAR FUEL TANKS"

PREPARED FOR

SOUTHWEST RESEARCH INSTITUTE
SAN ANTONIO, TEXAS 78284

P. O. No. 90573 IN SUPPORT OF
GOVERNMENT CONTRACT NO. DAAK70-79-C-0215

NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY, TERA GROUP
RESEARCH AND DEVELOPMENT DIVISION
SOCORRO, NEW MEXICO 87801
2 MAY 1980

APC TEST AZ0418A0

DATE: 18 APRIL 1980

TIME: 1430 MST

TEMPERATURE: 84°F (ambient)

WIND: LIGHT AND VARIABLE

TEST FUEL: NEAT DIESEL

FUEL TEMPERATURE: 170°F

SHAPE CHARGE: TYPE 3.2 PRECISION

TARGET VEHICLE: ALUMINUM TYPE ARMOURED PERSONNEL CARRIER

TEST CONDITIONS

An aluminum fuel cell containing 60 U.S. gallons of neat diesel fuel was positioned adjacent to the inside wall of the APC and secured in place using two 1/16"x2.0"x72.0" mild steel straps. Camera installations consisted of one each high-speed and real-time for interior coverage and one each high-speed and real-time for exterior coverage. Additional data gathering equipment consisted of one thermocouple and one pressure transducer inside the APC using a strip chart recorder for monitoring. For this test the APC ramp was closed, and the interior fan was off.

TEST RESULTS

There was a large fireball at detonation followed by an intense uncontrolled afterfire. The fuel cell lower restraining strap was broken and the cell was blown loose. All fuel was expelled. Interior temperature measured 1050°F and interior pressure indicated 12 psi.

APC TEST AZ0421A0

DATE:	21 APRIL 1980
TIME:	1130 MST
TEMPERATURE:	75°F (ambient)
WIND:	8G15 MPH, SOUTH
TEST FUEL:	SOUTHWEST RESEARCH FRF-A
FUEL TEMPERATURE:	170°F
SHAPE CHARGE:	TYPE 3.2 PRECISION
TARGET VEHICLE:	ALUMINUM TYPE ARMOURED PERSONNEL CARRIER

TEST CONDITIONS:

An aluminum fuel cell containing 60 U.S. gallons at Southwest Research FRF-A fuel was positioned adjacent to the inside wall of APC and secured in place using two 1/16"x2.0"x72.0" mild steel straps. Camera installations consisted of one each high-speed and real-time for interior coverage and one each high-speed and real-time for exterior coverage. Additional data gathering equipment consisted of one thermocouple and one pressure transducer inside the APC using a strip chart recorder for monitoring. For this test, the APC ramp was closed, aft and top hatches were closed, and the interior fan was on.

TEST RESULTS:

There was a large fireball at detonation followed by a small isolated afterfire in the camera compartment. Both fuel cell restraining straps were broken and the cell was blown loose. All fuel was expelled. Interior temperature measured 650°F and interior pressure indicated 11 psi.

APC TEST AZ0421B0

DATE:	21 APRIL 1980
TIME:	1630 MST
TEMPERATURE:	82°F (ambient)
WIND:	15G25, SOUTH
TEST FUEL:	NEAT DIESEL
FUEL TEMPERATURE:	170°F
SHAPE CHARGE:	TYPE 3.2 PRECISION
TARGET VEHICLE:	ALUMINUM TYPE ARMOURED PERSONNEL CARRIER

TEST CONDITIONS

An aluminum fuel cell containing 60 U.S. gallons of neat diesel fuel was positioned adjacent to the inside wall of the APC and secured in place using two 1/16"x2.0"x72.0" mild steel straps. Camera installations consisted of one each high-speed and real-time for interior coverage and one each high-speed and real-time for exterior coverage. Additional data gathering equipment consisted of one thermocouple and one pressure transducer inside the APC using a strip chart recorder for monitoring. For this test, the APC ramp was open, the top hatch was closed, and the interior fan was on.

TEST RESULTS

There was a large fireball at detonation followed by an intense afterfire. The fuel cell lower restraining strap was broken and the cell blown loose. All fuel was expelled. Interior temperature measured 1200°F and interior pressure indicated 11 psi.

APC TEST AZ0422A0

DATE:	22 APRIL 1980
TIME:	1145 MST
TEMPERATURE:	70°F (ambient)
WIND:	10G20 MPH, SOUTH
TEST FUEL:	SOUTHWEST RESEARCH FRF-A
FUEL TEMPERATURE:	170°F
SHAPE CHARGE:	TYPE 3.2 PRECISION
TARGET VEHICLE:	ALUMINUM TYPE ARMOURED PERSONNEL CARRIER

TEST CONDITIONS

An aluminum fuel cell containing 60 U.S. gallons of Southwest Research FRF-A fuel was positioned adjacent to the inside wall of the APC and secured in place using two 1/16"x2.0"x72.0" mild steel straps. Camera installations consisted of one each high-speed and real-time for interior coverage and one each high-speed and real-time for exterior coverage. Additional data gathering equipment consisted of one thermocouple and one pressure transducer inside the APC using a strip chart recorder for monitoring. For this test, the APC ramp was down, the top hatch was closed, and the interior fan was on.

TEST RESULTS

There was a large fireball at detonation with no subsequent after-fire. The fuel cell lower restraining strap was broken and the cell was blown loose. All fuel was expelled. Interior temperature measured 150°F and interior pressure indicated 25.5 psi.

M-48 TEST AZ0422B0

DATE:	22 APRIL 1980
TIME:	1630 MST
TEMPERATURE:	84°F (ambient)
WIND:	15G25 MPH, SOUTH
TEST FUEL:	NEAT DIESEL
FUEL TEMPERATURE:	170°F
SHAPE CHARGE:	TYPE 3.2 PRECISION
TARGET VEHICLE:	M-48-A1 MAIN BATTLE TANK

TEST CONDITIONS

An original M-48 steel fuel cell containing 80 U.S. gallons of neat diesel fuel was used in this test. The M-48 engine was in place alongside the cell. One each high-speed and real-time cameras were used for exterior coverage only and thermocouple and pressure transducer instrumentation was mounted inside the gun compartment and monitored by strip chart recorder. Fragment entry was from the port side.

TEST RESULTS

There was a large fireball at detonation followed by a slow burning but intense afterfire. Fragments exited the fuel cell expelling all fuel into the engine compartment. Interior temperature and pressure were not recorded.

M-48 TEST AZ0424A0

DATE:	24 APRIL 1980
TIME:	1430 MST
TEMPERATURE:	78°F (ambient)
WIND:	15G25 MPH, SOUTH
TEST FUEL:	SOUTHWEST RESEARCH FRF-A
FUEL TEMPERATURE:	170°F
SHAPE CHARGE:	TYPE 3.2 PRECISION
TARGET VEHICLE:	M-48-A1 MAIN BATTLE TANK

TEST CONDITIONS

An original M-48 steel fuel cell containing 40 U.S. gallons of Southwest Research FRF-A fuel was used in this test. The M-48 engine was in place alongside the cell. One each high-speed and real-time cameras were used for exterior coverage only and thermocouple and pressure transducer instrumentation was mounted inside the gun compartment and monitored by strip chart recorder. Fragment entry was from the starboard side.

TEST RESULTS

There was a large fireball at detonation followed by a small isolated afterfire below the oil-filled engine air cleaner. Fragments exited the fuel cell expelling all but ≈ four gallons of fuel. Interior pressure measured 3.25 psi. Interior temperature was not recorded.

M-48 TEST AZ0425A0

DATE:	25 APRIL 1980
TIME:	1500 MST
TEMPERATURE:	65°F (ambient)
WIND:	10G15 MPH, SOUTH
TEST FUEL:	SOUTHWEST RESEARCH FRF-A
FUEL TEMPERATURE:	170°F
SHAPE CHARGE:	TYPE 3.2 PRECISION
TARGET VEHICLE:	M-48-A1 MAIN BATTLE TANK

TEST CONDITIONS

An original M-48 steel fuel cell containing 85 U.S. gallons of Southwest Research FRF-A fuel was used in this test. The M-48 engine was in place alongside the cell. One each high-speed and real-time cameras were used for exterior coverage only and thermocouple and pressure transducer instrumentation was mounted inside the gun compartment and monitored by strip chart recorder. Fragment entry was from the portside.

TEST RESULTS

There was a large fireball at detonation with no subsequent afterfire. Fragments exited the fuel cell expelling all but ≈ ten gallons of fuel. Interior pressure and temperature were not recorded.

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US ARMY YUMA PROVING GROUND
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MICHIGAN ARMY MISSILE PLANT
OFC OF PROJ MGR, XM-1 TANK SYS
ATTN DRCPM-GCM-S 1
WARREN MI 48090

MICHIGAN ARMY MISSILE PLANT
PROG MGR, FIGHTING VEHICLE SYS
ATTN DRCPM-FVS-SE 1
WARREN MI 48090

PROJ MGR, M60 TANK DEVELOPMENT
ATTN DRCPM-M60-E 1
WARREN MI 48090

PROG MGR, M113/M113A1 FAMILY
OF VEHICLES
ATTN DRCPM-M113 1
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PROJ MGR, MOBILE ELECTRIC POWER
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Table 3.1b. List of Monitoring Equipment

Site No.	Shelter No.	Shelter Dimensions	Parameter Measured	Equipment Instrument Manufacturer	Voltage Output
1	Self Propelled EPA #313	27'x8'x 14'*	NO, NO_x	Thermo Electron Company (TECO)	10V
				Bendix	10V 1V
			Single pen strip chart recorders (SCR) for each parameter.		
2 Background	Self Propelled EPA #376	27'x8'x30'**	CO	Bendix	10V
			O_3	Dasibi	
			HC	Bendix	1V
			NO_x	Bendix	1V
			Wind Direction & Velocity	Climatronics	
			Single pen strip chart recorders (SCR) for each parameter which is also input into data processing computer.		
3	Trailer EPA #577	8'x14'x14'*	CO	Bendix	10V 1V
			NO_x NO	TECO	10V
			Wind Direction & Velocity	Climet	
			Wind Direction & Velocity (2 Dimensions)	MRI Vector Vane	
			Temperature and Temperature Gradient	Climet	
			Single pen SCR for each paramter.		
4	Self Propelled EPA #315	Same as Site 1	NO_x	Bendix	1V
			CO	Bendix	10V 1V
			Single pen SCR for each parameter.		
			4 multi pen SCR coordinated to common time reference to simultaneously record concentrations at Sites 1, 3, 4, 5, 6. Data logger computer to record 15 channels of data from Sites 1, 3, 4, 5, 6.		
5	Trailer EPA #575	Same as Site 3	NO_x	Bendix	1V
			Single pen SCR for each parameter		
6	Trailer EPA #576	Same as Site 3	CO	Bendix	10V
			CO	Energetic Sciences Co. (2), mobile	
			HC	Beckman 400	
			Single pen SCR for each parameter		

*Includes Air Intake Probe.

**Includes 22 foot high wind set.

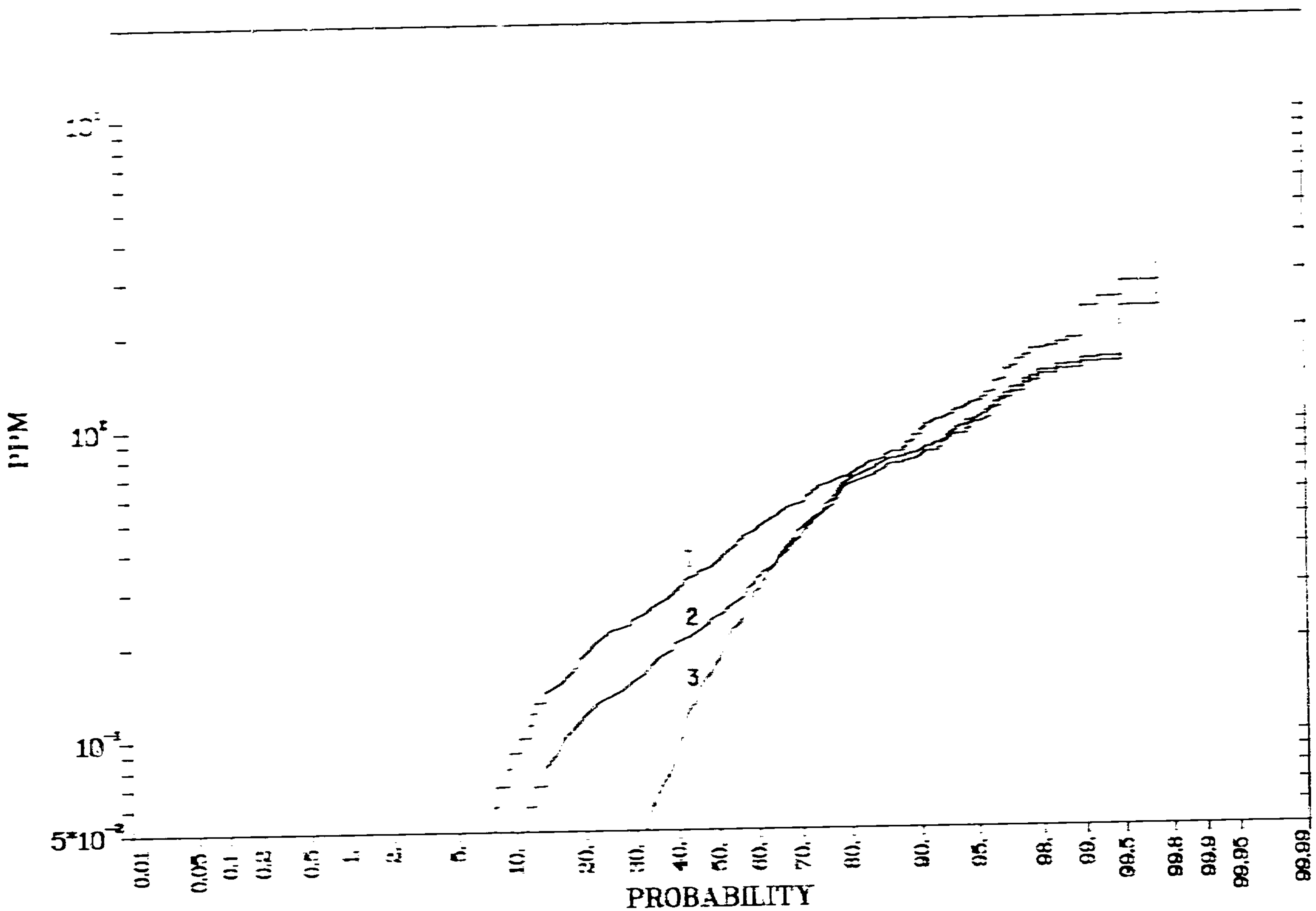

Fig. 3.9. Cumulative Frequency Distributions of Hourly CO Concentrations at Station 4. The three curves are explained in the text.

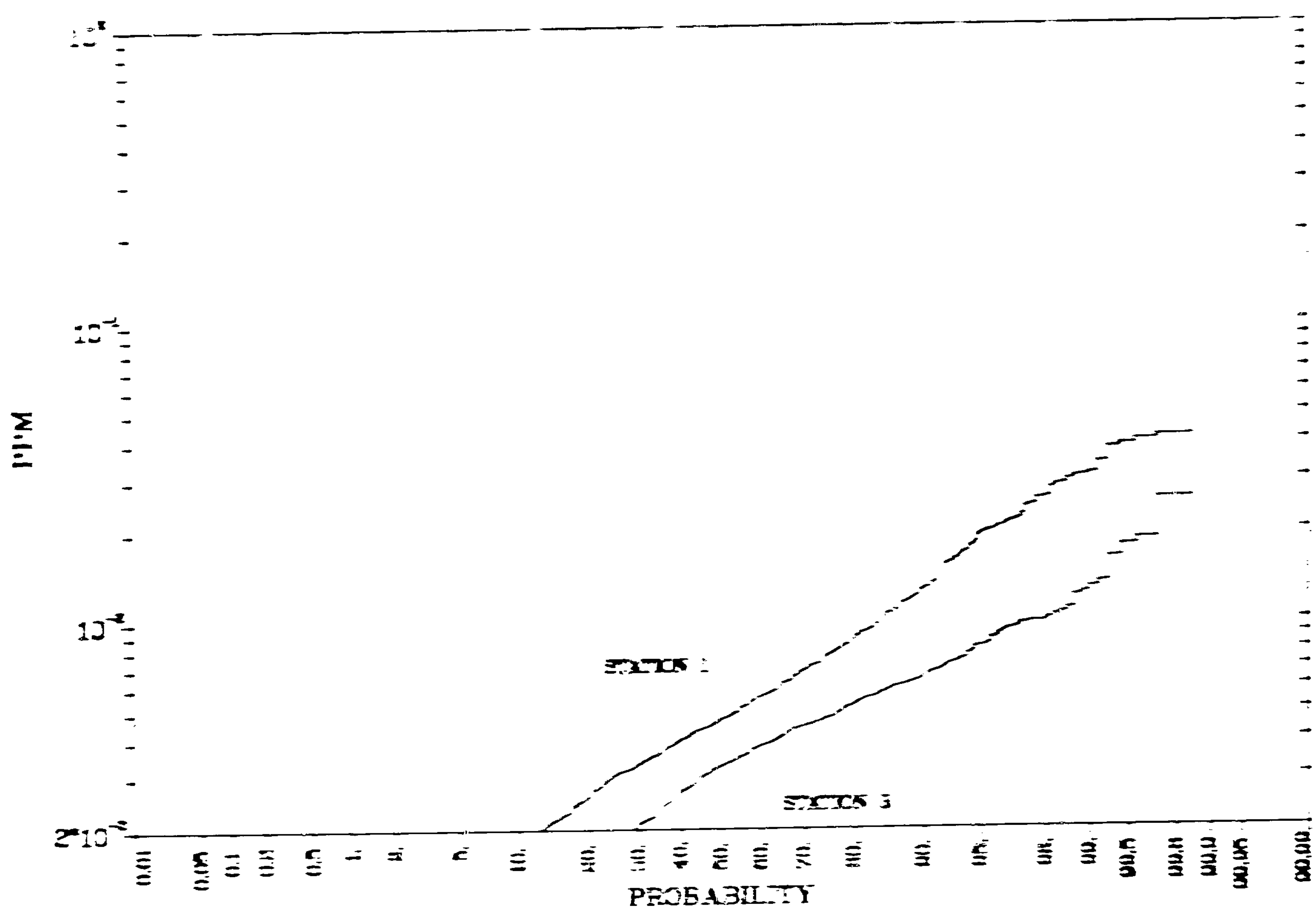

Fig. 3.[illegible]. Cumulative Frequency Distributions of Hourly Background Subtracted $NO_2 \equiv NO_x - NO$ Concentrations at Stations 1 and 3.